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# Investigation on the Practicality of Developing Reduced Thermal Models

Giancarlo Lombardi
*Florida International University*

Kan Yang
*NASA Goddard Space Flight Center*
*Thermal Engineering Branch*

# Outline

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# Introduction

- Why thermal models?
  - To simulate on-orbit thermal response of spacecraft
- Why reduced models?
  - Reduce runtime from detailed models
  - Quick analysis turnaround
- Expected outcome
  - Decreased runtime
  - Loss in accuracy
- Does the decreased runtime to obtain results compensate for the additional effort placed on producing the reduced models?

# Detailed vs. Reduced

- Detailed model
  - A thermal model developed with the intention of fully capturing the thermal responses of the spacecraft in its on-orbit environment
- Reduced model
  - Simplified thermal model (less nodes and surfaces) produced with the intention of reducing simulation runtime
  - Reduced models are created to be within acceptable error bounds (as defined by project) of the detailed model
- Thermal models used for this study were obtained from colleagues at GSFC
  - Level of error in reduced model may have been justified when the model was built
  - Reduced model may have been biased to produce more conservative results with respect to detailed model

# Methodology

- Hardware Specifications:
  - Processor: Intel Core i7 vPro, 3.7 GHz
  - System: 64-bit OS
  - Ram: 8.0 GB

- Current work focuses on:
  - Comparison of runtime vs. nodal reduction between reduced and detailed models across projects
  - Comparison of nodal reduction vs. accuracy across six major components of each spacecraft/instrument pair

# Methodology

1. Set up Case Set in Thermal Desktop (TD)
   - Integrate Detailed and Reduced instrument models to spacecraft bus
   - Hot and Cold case; 5 orbits transient run

2. Generate SINDA .inp file and run solver
   - Record Start and end times
   - NOTE: SINDA only uses one core (NO parallel processing)

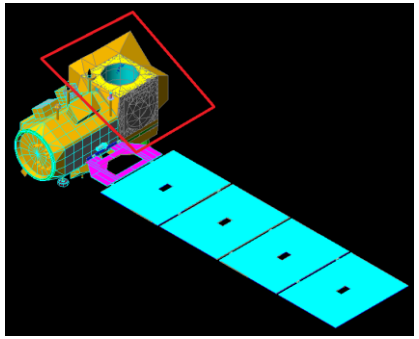
3. Repeat each TD case set run three times to obtain an average runtime
   - Calculate total run time for each SINDA run (runtime = end - start time)

4. Post-process using Thermal Analysis Results Processor (TARP)
   - Generate Temperature tables
   - Incorporate Weighting file to mitigate effect of components with low thermal masses

5. Compare Reduced model data with Detailed model data
   - Record Maximum Temperature and Heat difference for six major components

# Ice, Cloud, and Land Elevation Satellite 2 (ICESat-2)

- Launch Date: 2017
- Mission: Measure ice cap elevation and thickness
- Investigation Focus:
  Advanced Topographic Laser Altimeter System (ATLAS)
  - Emits visible green laser pulses providing dense cross-track sampling to help scientists determine ice sheet thickness and slope
- ICESat-2 bus integrated with reduced ATLAS instrument model
  - Independently ran both reduced and detailed ATLAS models and compared with the total runtime for integrated ICESat-2 bus



**Full ICESat-2 Thermal Model (ATLAS in red box)**

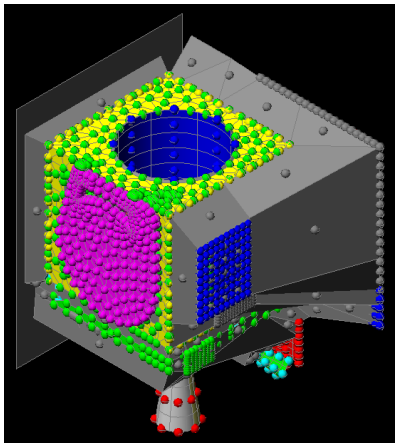
# ATLAS Reduced vs. Detailed Model Analysis

- Reduced Model Development Time: 120 hr
- Nodal Count
  - Spacecraft: 10,359
  - Detailed ATLAS: 11,737
  - Reduced ATLAS: 6,392

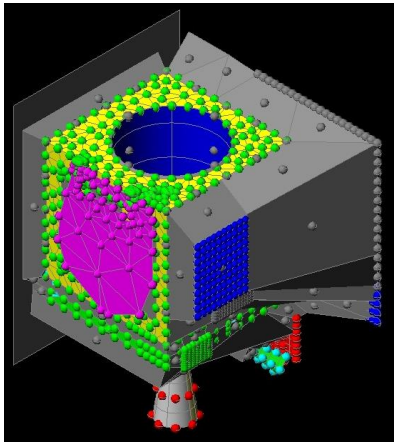
**Nodal Reduction**
**ATLAS: 45.5%**
**Integrated: 24.2%**

| Node Percent Reduction | | | |
|---|---|---|---|
| **Component** | **Detailed Nodes** | **Reduced Nodes** | **Reduction Percentage** |
| LRS_ORAD | 138 | 138 | 0.0 |
| LTCS_RAD | 914 | 914 | 0.0 |
| MEB_RAD | 140 | 140 | 0.0 |
| PDU_RAD | 200 | 13 | 93.5 |
| PBC | 227 | 6 | 97.4 |
| STARTPD | 2 | 2 | 0.0 |

| Case | Complexity | Time (min) | Time Reduction |
|---|---|---|---|
| **Hot** | Detailed | 106.4 | 65.7 min **(62%)** |
| | Reduced | 40.7 | |
| **Cold** | Detailed | 62.6 | 30.3 min **(48.4%)** |
| | Reduced | 32.3 | |



**ATLAS Detailed Thermal Model**



**ATLAS Reduced Thermal Model**

# ATLAS Data

## Temperature [°C]

| ATLAS - Hot Case | | | |
|---|---|---|---|
| **Component** | **Detailed** | **Reduced** | **Δ T** |
| LRS_ORAD | 13.9 | 13.9 | **0** |
| LTCS_RAD | -15.6 | -16.2 | **-0.6** |
| MEB_RAD | 25.9 | 26.1 | **0.2** |
| PBC | 19.9 | 20.2 | **0.3** |
| PDU_RAD | 23.7 | 23.6 | **-0.1** |
| STARTPD | 25.2 | 23.4 | **-1.8** |

| ATLAS - Cold Case | | | |
|---|---|---|---|
| **Component** | **Detailed** | **Reduced** | **Δ T** |
| LRS_ORAD | 20.7 | 20.9 | **0.2** |
| LTCS_RAD | -48.0 | -48.9 | **-0.9** |
| MEB_RAD | 5.6 | 5.8 | **0.2** |
| PBC | 0.4 | 0.6 | **0.2** |
| PDU_RAD | -12.0 | -12.0 | **0** |
| STARTPD | 4.7 | 4.0 | **-0.7** |

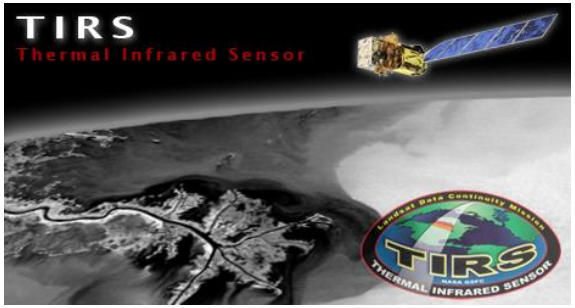
## Heat [W]

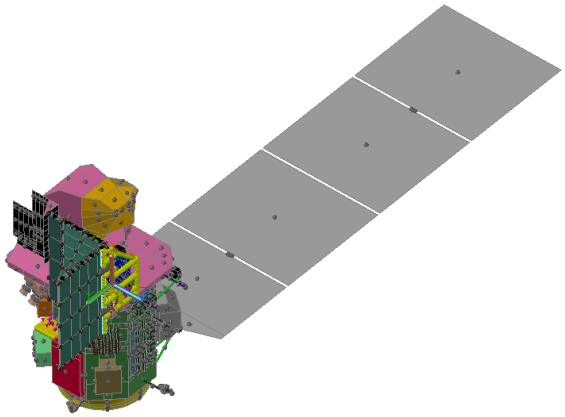
| ATLAS - Hot Case | | | |
|---|---|---|---|
| **Component** | **Detailed** | **Reduced** | **Δ Q** |
| LRS_ORAD | 6.3 | 6.9 | **0.6** |
| LTCS_RAD | 145.0 | 145.1 | **0.1** |
| MEB_RAD | 34.6 | 34.7 | **0.1** |
| PBC | 0.0 | 0.0 | **0** |
| PDU_RAD | 44.6 | 44.6 | **0** |
| STARTPD | 4.0 | 4.0 | **0** |

| ATLAS - Cold Case | | | |
|---|---|---|---|
| **Component** | **Detailed** | **Reduced** | **Δ Q** |
| LRS_ORAD | 9.5 | 14.3 | **4.8** |
| LTCS_RAD | 115.5 | 119.9 | **4.4** |
| MEB_RAD | 22.0 | 22.0 | **0** |
| PBC | 0.0 | 0.0 | **0** |
| PDU_RAD | 17.9 | 17.9 | **0** |
| STARTPD | 3.0 | 3.0 | **0** |

# Landsat 8

- Launch Date: February 11, 2013
- Mission: Record temperature changes of the Earth's polar and terrestrial regions
- Investigation Focus:
  Thermal Infrared Sensor (TIRS)
  - Measures land surface temperature in two infrared thermal bands with a new technology that applies quantum physics to detect heat
- Comparison between reduced TIRS integrated on bus vs. detailed TIRS integrated on bus



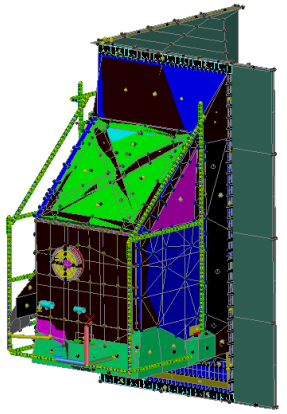



**Full Landsat Thermal Model**

# TIRS Reduced vs. Detailed Model Analysis

- Reduced Model Development Time: 1000 hr
- Nodal Count
  - Spacecraft: 1,415
  - Detailed TIRS: 18,529
  - Reduced TIRS: 1,556

**Nodal Reduction**
**TIRS: 91.6%**
**Integrated: 85.1%**



TIRS Detailed Thermal Model

TIRS Reduced Thermal Model

| Node Percent Reduction | | | |
|---|---|---|---|
| **Component** | **Detailed Nodes** | **Reduced Nodes** | **Reduction Percentage** |
| FPE | 158 | 23 | 85.4 |
| STAGE2 | 78 | 5 | 93.6 |
| STAGE1 | 108 | 6 | 94.4 |
| BBCAL | 63 | 3 | 95.2 |
| STAGE3 | 228 | 4 | 98.2 |
| SSM | 526 | 6 | 98.9 |

| Case | Complexity | Time (min) | Time Reduction |
|---|---|---|---|
| **Hot** | Detailed | 31.7 | -4.2 min **(-13.2%)** |
| | Reduced | 35.9 | |
| **Cold** | Detailed | 47.5 | 16.4 min **(34.5%)** |
| | Reduced | 31.1 | |

# TIRS DATA

## Temperature [°C]

| TIRS - Hot Case | | | |
|---|---|---|---|
| **Component** | **Detailed** | **Reduced** | **Δ T** |
| STAGE 1 | -84.3 | -84.0 | **0.3** |
| STAGE 2 | -85.5 | -85.4 | **0.1** |
| STAGE 3 | -86.8 | -86.8 | **0.0** |
| SSM | 2.4 | -1.9 | **0.5** |
| BBCAL | 44.1 | 44.9 | **-0.8** |
| FPE | 9.0 | 9.5 | **-0.5** |

| TIRS - Cold Case | | | |
|---|---|---|---|
| **Component** | **Detailed** | **Reduced** | **Δ T** |
| STAGE 1 | -84.6 | -84 | **0.6** |
| STAGE 2 | -85.7 | -85.4 | **0.3** |
| STAGE 3 | -86.9 | -86.8 | **0.1** |
| SSM | -13.3 | -16 | **-2.7** |
| BBCAL | -3.6 | -3.8 | **-0.2** |
| FPE | 7.4 | 8.9 | **-1.5** |

## Heat [W]

| TIRS - Hot Case | | | |
|---|---|---|---|
| **Component** | **Detailed** | **Reduced** | **Δ Q** |
| Telescope Stage | 1.3 | 0.8 | **-0.5** |
| Telescope | 0.4 | 0.1 | **-0.3** |
| SSM | 3.7 | 2.0 | **-1.7** |
| FPE | 4.1 | 1.6 | **-2.5** |
| BBCAL | 1.9 | 4.9 | **3.0** |

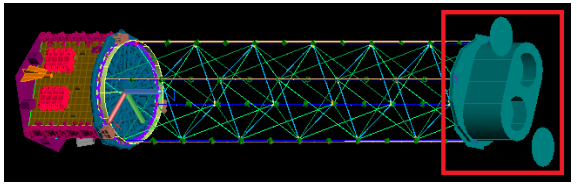
| TIRS - Cold Case | | | |
|---|---|---|---|
| **Component** | **Detailed** | **Reduced** | **Δ Q** |
| Telescope Stage | 2.1 | 2.7 | **0.6** |
| Telescope | 0.6 | 0.7 | **0.1** |
| SSM | 0.0 | 7.7 | **7.7** |
| FPE | 7.6 | 7.7 | **0.1** |
| BBCAL | 1.2 | 4.7 | **3.5** |

# Gravity and Extreme Magnetism Small Explorer (GEMS)

- Launch Date: CANCELLED
- Mission: Observe strong gravitational fields around black holes and magnetic fields around pulsars

- Investigation Focus: Mirror Optical Bench (MOB)
  - Contains two mirror assemblies which detect x-rays with energies between 2,000 and 10,000 eV

- GEMS bus integrated with reduced MOB model
  - Independently ran both reduced and detailed mirror models and compared with the total runtime for GEMS bus with reduced MOB model

**Full GEMS Thermal Model (Mirror in red box)**

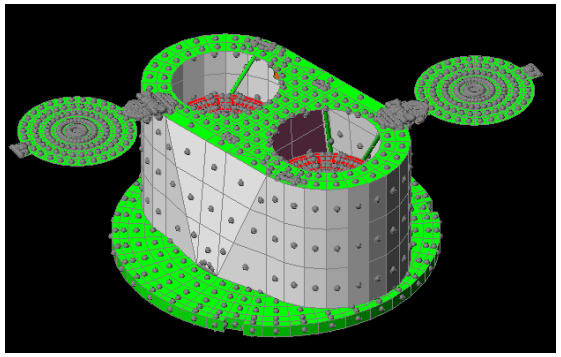
# MOB Reduced vs. Detailed Model Analysis

- Reduced Model Development Time: 80 hr
- Nodal Count
  - Spacecraft: 6,080
  - Detailed MOB: 17,025
  - Reduced MOB: 654

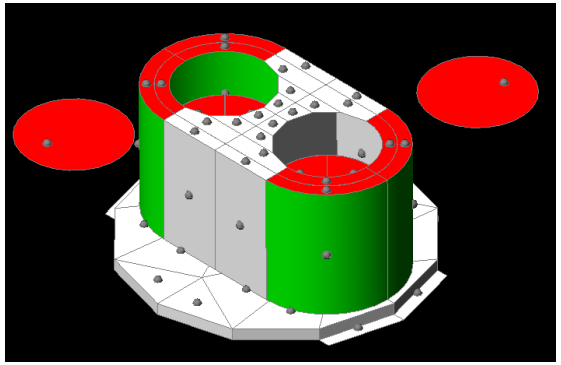
**Nodal Reduction**
**MOB: 96.2%**
**Integrated: 70.9%**

| Node Percent Reduction | | | |
|---|---|---|---|
| **Component** | **Detailed Nodes** | **Reduced Nodes** | **Reduction Percentage** |
| SS_DECK | 216 | 32 | 85.2 |
| MOBDECK | 768 | 68 | 91.1 |
| PMIRR1 | 1980 | 56 | 97.2 |
| PMIRR2 | 1980 | 56 | 97.2 |
| TOP_TS_1 | 258 | 6 | 97.7 |
| TOP_TS_2 | 258 | 6 | 97.7 |

| Case | Complexity | Time (min) | Time Reduction |
|---|---|---|---|
| **Hot** | Detailed | 444.3 | 129.3 min **(29.1%)** |
| | Reduced | 315 | |
| **Cold** | Detailed | 416.3 | 136 min **(32.7%)** |
| | Reduced | 280.3 | |



**Mirror Detailed Thermal Model**



**Mirror Reduced Thermal Model**

# GEMS Data

## Temperature [°C]

| GEMS - Hot Case | | | |
|---|---|---|---|
| **Component** | **Detailed** | **Reduced** | **Δ T** |
| MOBDECK | -56.8 | -57.6 | **-0.8** |
| PMIRR1 | -61.6 | -45.5 | **16.1** |
| PMIRR2 | -61.8 | -45.9 | **15.9** |
| SS_DECK | -56.6 | -52.6 | **4.0** |
| TOP_TS_1 | -60.4 | -44.3 | **16.1** |
| TOP_TS_2 | -60.7 | -44.7 | **16.0** |

| GEMS - Cold Case | | | |
|---|---|---|---|
| **Component** | **Detailed** | **Reduced** | **Δ T** |
| MOBDECK | -74.0 | -75.0 | **-1.0** |
| PMIRR1 | -80.9 | -79.0 | **1.9** |
| PMIRR2 | -79.2 | -69.9 | **9.3** |
| SS_DECK | -82.1 | -80.1 | **2.0** |
| TOP_TS_1 | -81.2 | -80.3 | **0.9** |
| TOP_TS_2 | -79.4 | -71.9 | **7.5** |

## Heat [W]

| GEMS - Hot Case | | | |
|---|---|---|---|
| **Component** | **Detailed** | **Reduced** | **Δ Q** |
| MOBDECK | 90.1 | 67.7 | **-22.4** |
| PMIRR1 | 0.0 | 0.0 | **0** |
| PMIRR2 | 0.0 | 0.0 | **0** |
| SS_DECK | 14.8 | 4.7 | **-0.1** |
| TOP_TS_1 | 0.9 | 0.8 | **-0.1** |
| TOP_TS_2 | 0.8 | 0.8 | **0** |

| GEMS - Cold Case | | | |
|---|---|---|---|
| **Component** | **Detailed** | **Reduced** | **Δ Q** |
| MOBDECK | 66.9 | 50.4 | **-16.5** |
| PMIRR1 | 0.0 | 0.0 | **0** |
| PMIRR2 | 0.0 | 0.0 | **0** |
| SS_DECK | 8.2 | 8.1 | **-0.1** |
| TOP_TS_1 | 0.3 | 0.3 | **0** |
| TOP_TS_2 | 0.3 | 0.3 | **0** |

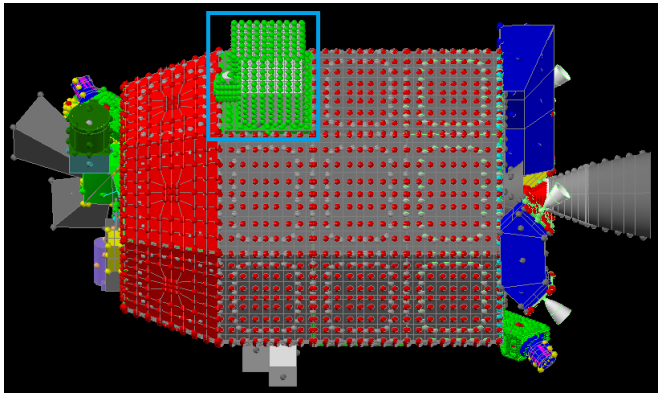
# Lunar Atmosphere and Dust Environment Explorer (LADEE)

- Launch Date: September 2013
- Mission: Analyze the Moon's thin exosphere and the lunar dust environment
- Investigation Focus:
  Neutral Mass Spectrometer (NMS)
  - NMS instrument measures variations in chemistry of the lunar atmosphere at different altitudes and orbits
- Bus with reduced instrument models used as baseline
  - NMS detailed model incorporated into reduced bus model


# NMS Reduced vs. Detailed Model Analysis

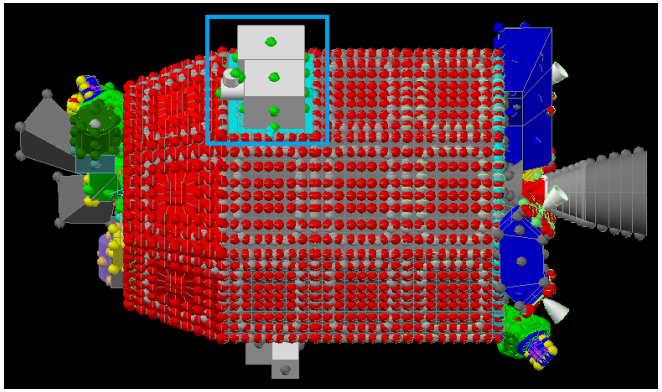
- Reduced Model Development Time: 80 hr
- Nodal Count
  - Spacecraft: 14,750
  - Detailed NMS: 1,040
  - Reduced NMS: 35

**Nodal Reduction**
**NMS: 96.6%**
**Integrated: 6.4%**



NMS Detailed Thermal Model

| Node Percent Reduction | | | |
|---|---|---|---|
| **Component** | Detailed Count | Reduced Count | Reduction Percentage |
| INTP | 34 | 4 | 88.2 |
| BSPL | 141 | 12 | 91.5 |
| CPNL | 156 | 9 | 94.2 |
| QMS | 119 | 4 | 96.6 |
| MEB | 431 | 6 | 98.6 |



NMS Reduced Thermal Model

| Case | Complexity | Time (min) | Time Reduction |
|---|---|---|---|
| **Hot** | Detailed | 57 | 12 min **(21.1%)** |
| | Reduced | 45 | |
| **Cold** | Detailed | 61.7 | 8.7 min **(14.1%)** |
| | Reduced | 53 | |

# NMS DATA

## Temperature [°C]

| LADEE - Hot Case | | | |
|---|---|---|---|
| **Component** | **Detailed** | **Reduced** | **Δ T** |
| BSPL | 37.4 | -16.1 | **-53.5** |
| CPNL | -21.3 | -21.3 | **0.0** |
| INTP | 12.9 | 3.8 | **-9.1** |
| MEB | -42.7 | -21.9 | **20.8** |
| QMS | 14.9 | -27.0 | **-41.9** |

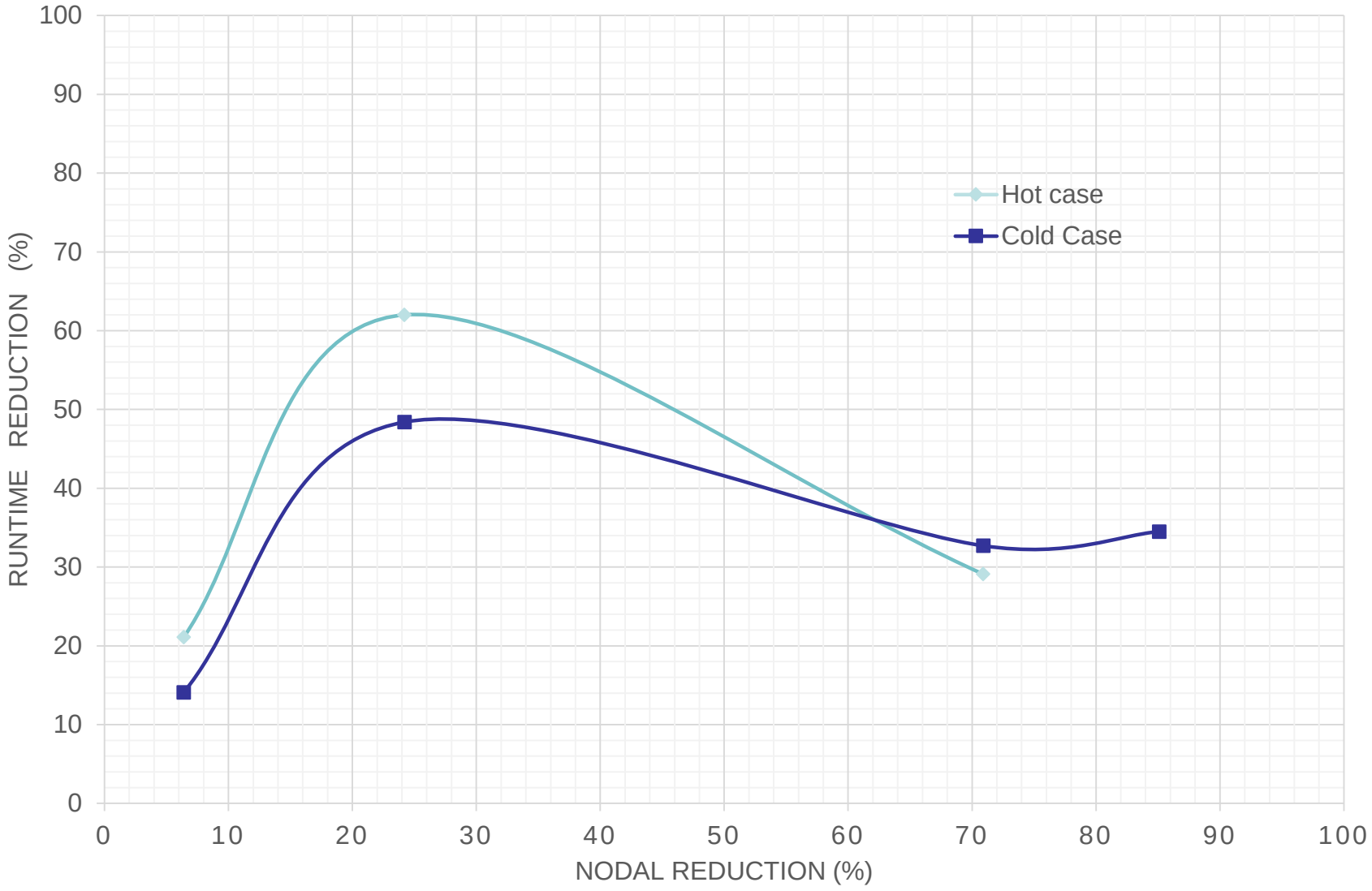
| LADEE - Cold Case | | | |
|---|---|---|---|
| **Component** | **Detailed** | **Reduced** | **Δ T** |
| BSPL | -23.9 | -19.5 | **4.4** |
| CPNL | -45.3 | -22.4 | **22.9** |
| INTP | 10.1 | 10.8 | **0.7** |
| MEB | -61.9 | -22.8 | **39.1** |
| QMS | -29.3 | -30.2 | **-0.9** |

## Heat [W]

| LADEE - Hot Case | | | |
|---|---|---|---|
| **Component** | **Detailed** | **Reduced** | **Δ Q** |
| BSPL | 0.0 | 4.0 | **4.0** |
| CPNL | 0.0 | 22.0 | **22.0** |
| INTP | 9.8 | 9.6 | **-0.2** |
| MEB | 5.2 | 13.9 | **8.7** |
| QMS | 3.9 | 4.3 | **0.4** |

| LADEE - Cold Case | | | |
|---|---|---|---|
| **Component** | **Detailed** | **Reduced** | **Δ Q** |
| BSPL | 0.0 | 2.5 | **2.5** |
| CPNL | 0.0 | 10.4 | **10.4** |
| INTP | 7.0 | 6.7 | **-0.3** |
| MEB | 2.1 | 23.5 | **21.4** |
| QMS | 4.7 | 5.3 | **0.6** |

# Effects of Nodal Reduction on Runtime



# Break-Even Analysis

- Definition: Number of reduced model simulation runs needed to match the development time
- Objective: Justify development time
- Compiling known data:

| Mission | Development Time (hours) | Hot Case Time Reduction (minutes) | Cold Case Time Reduction (minutes) |
|---|---|---|---|
| ICESAT-2 | 120 | 65.7 | 30.25 |
| Landsat 8 | 1000 | -4.2 | 16.4 |
| GEMS | 80 | 129.3 | 136 |
| LADEE | 80 | 12 | 8.7 |

| Break Even Run Count | | |
|---|---|---|
| Mission | **Hot** | **Cold** |
| ICESAT-2 | 110 | 239 |
| Landsat 8 | -- | 3659 |
| GEMS | 38 | 36 |
| LADEE | 400 | 552 |

# Accuracy Loss

- Accuracy loss obtained across all reduced models. Maximum ΔT and ΔH for each mission:

| | LADEE | ICESat-2 | GEMS | Landsat 8 |
|---|---|---|---|---|
| Reduction | 6.4% | 24.2% | 70.9% | 85.1% |
| Hot [°C] | 53.5 | 1.8 | 16.1 | 0.8 |
| Cold [°C] | 39.1 | 0.9 | 9.3 | 2.7 |
| Hot [W] | 22 | 0.6 | 22.4 | 3.0 |
| Cold [W] | 21.4 | 4.8 | 16.5 | 7.7 |

- No trend established
  - No correlation between nodal reduction and accuracy loss

# Observations from Analysis Results

- Runtime for hot cases generally greater than cold cases
  - Greater inputs to energy balance equation (environmental flux)
  - However, some models have slower cold case runtime: this could be due to longer time needed to resolve heater power
- TIRS **detailed** hot case runtime actually faster than **reduced** model runtime despite having 671% more nodes
  - Perhaps numerical instability (reduction in areas of large thermal gradients) in reduced model led to slower runtime
  - Since computer hardware used for solving these cases had large amounts of memory, this could also be due to greater capacity of computer to iteratively solve energy balance per timestep, regardless of matrix size passed in
- Overall, there is not a linear reduction between runtime and nodal count

# Conclusion

- Given break-even analysis, development of reduced models are justified only if reduced model sees intensive use
  - With increasing computer power, the difference in runtime does not justify time needed for development of reduced model
  - However, the need may arise to waive the time reduction penalty (e.g. fast results for an in-flight maneuver)

- No clear correlation between loss of accuracy and nodal reduction
  - Highly dependent on quality of reduced model developed

# Lessons Learned

- Improve book-keeping of model development
  - Record development time
  - Provide compatible models
  - Consistency of Model Development
- Use computer dedicated to running simulations
  - Avoid using same computer during simulations
- Select a more representative pool of reduced models
  - Varying levels of model reduction
  - Define the established runtime reduction trend

# QUESTIONS?